

Exploration of Spin-down Rate of Neutron Star in High Mass X-ray Binaries

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ABSTRACT

We use the evolutionary population synthesis method to investigate the statistical properties of the wind-fed neutron star (NS) compact ($P_{\text{orb}} < 10$ days) high-mass X-ray binaries (HMXBs) in our Galaxy, based on different spin-down models. We find that the spin-down rate in the supersonic propeller phase given by **assuming that the surrounding material is treated as forming a quasi-static atmosphere or by assuming that the characteristic velocity of matter and the typical Alfvén velocity of material in the magnetospheric boundary layer are comparable to the sound speed in the external medium** is too low to produce the observed number of compact HMXBs. We also find that the models suggested by **assuming that the infalling material is ejected with the corotation velocity at the magnetospheric radius when the magnetospheric radius is larger than the corotation radius and by simple integration of the magnetic torque over the magnetosphere** with a larger spin-down rate than that given by Davies & Pringle (1981) or Illarionov & Sunyaev (1975) can predict a reasonable number of observed wind-fed NS compact HMXBs. Our calculated results indicate that subsonic propeller phase may not exist at all by comparing with the observed particular distributions of wind-fed NS compact HMXBs in the $P_s - P_{\text{orb}}$ diagram. However, the spin-down rate suggested by Wang & Robertson (1985); Dai, Liu & Li (2006); Jiang & Li (2005) and that given by Davidson & Ostriker (1973) both seem reasonable to produce the observed distribution of wind-fed NS compact HMXBs in the $P_s - P_{\text{orb}}$ diagram. We cannot find which spin-down rate seems more reasonable from our calculations.

Key words: binaries: close — galaxy: stellar content— stars: evolution — stars: neutron— X-ray: binaries.

1 INTRODUCTION

HMXBs are composed of a compact object that orbits a massive ($> 10 M_{\odot}$) donor star. The X-ray emission is due to the accretion of matter from the donor star onto the compact companion (black hole or neutron star). In most cases, the donor stars do not fill their Roche lobes and the compact objects accrete from the stellar wind. Canonically, HMXBs can be roughly divided into two groups: supergiant binaries and Be/X-ray binaries. In the supergiant systems, either Roche-lobe or stellar wind accretion occurs, while in the Be systems commonly only

the latter process takes place since the Be star is well inside its Roche lobe (Tauris & van den Heuvel 2006). Be/X-ray binaries are both transient and persistent X-ray sources. Transient systems are characterized by type II outburst during which their flux increases by a factor of $10\text{--}10^4$ over the quiescent level. On the other side, persistent Be/X-ray binaries show a rather flat lightcurve, lower luminosity, longer spin and orbital periods (Reig 2011).

Supergiant Fast X-ray Transients (SFXT) unveiled in the last few years mainly thank to INTEGRAL observations of the Galactic plane are a new sub-class of supergiant HMXBs that display extreme flaring behaviour on short (\sim hour) timescales (Sguera et al. 2005, 2006; Negueruela et al. 2006). They host a massive OB supergiant

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star as identified by optical spectroscopy. The compact object is generally assumed to be a NS because of the broad band X-ray spectral shape (0.2–100 keV) strongly resembling those of accreting X-ray pulsars in classical HMXBs (White et al. 1995). A distinctive property of SFXTs is the high dynamic range, spanning three to five orders of magnitude, with sudden increases in luminosity from 10^{32} erg s^{-1} up to the flare peak luminosity (e.g. in’t Zand 2005). There are currently 10 confirmed and about as many candidate SFXTs (Sidoli 2011).

The INTEGRAL observatory appears to have discovered a class of compact high mass X-ray binaries **which are a new class of γ -ray sources for which a mechanism is presented by Bednarek (2009), i.e., accreting neutron stars inside binary systems.** These newly discovered massive binaries are compact with orbital periods between a few to several days. Some contain relatively slowly rotating NSs that may allow the material to penetrate the inner NS magnetosphere.

The spin-down rate of NS in a **wind-fed NS** HMXB has been investigated by many authors. The rate of loss of angular momentum of a NS, proposed by Illarionov & Sunyaev (1975), Fabian (1975), Wickramasinghe & Whelan (1975), is obtained by assuming that the characteristic velocity of matter carrying off the required energy and the typical Alfvén velocity of material in the magnetospheric boundary layer are comparable to the sound speed in the external medium. The rate, proposed by Davidson & Ostriker (1973), Kundt (1976), van den Heuvel (1978) is obtained by simple integration of the magnetic torque over the magnetosphere and equating this to an angular momentum loss from the star by assuming that the field lines at the magnetosphere are swept back through an angle of 45° . The most rapid spin-down rate, proposed by Shakura (1975), Lipunov & Shakura (1976), Holloway, Kundt & Wang (1978), is obtained by treating the particle striking the magnetosphere as independent particles, and by assuming that they are all accelerated to a characteristic velocity, comparable to the rotational speed of the magnetosphere which is much larger than the sound speed in the external medium. The comprehensive picture by assuming that the surrounding material is treated as forming a quasi-static atmosphere through which energy is transported was first drawn by Davies & Pringle (1981), whose model passes through four distinct phases as a NS slows down. Mori & Ruderman (2003) suggested that two parameters can classify many proposed propeller spin-down models. Many authors have derived the spin-down rate of propeller phase by assuming that the infalling material is ejected with the corotation velocity at the magnetospheric radius when the magnetospheric radius is larger than the corotation radius (Wang & Robertson 1985; Dai, Liu & Li 2006; Jiang & Li 2005). **Besides, a large number of authors (see, e.g., Spruit & Taam 1993; Rappaport et al. 2004; D’Angelo & Spruit 2010, 2012) have investigated the spin-down rate of NS accreting from a disk in a NS HMXB. Romanova et al. (2013) have studied accretion onto a star in the propeller regime by magnetohydrodynamic simulations.**

Though the propeller effect has been investigated extensively, there still remain large uncertainties about the efficiency of angular momen-

um loss during the propeller regime (see, e.g., Pringle & Rees 1972; Ikhsanov 2001). The investigations mentioned above were usually either theoretical or numerical. To better understand the spin-down mechanism of a NS, we should use an evolutionary population synthesis which incorporates the evolution of a neutron star’s spin. In the present paper, we describe a population synthesis study of the spin evolution of a NS in a massive binary. Obviously, it is very difficult to provide more stringent constraints on these spin-down models from theory. However, we can give more constraints on the spin-down rate by comparing the calculated results based on the evolutionary population synthesis method by adopting different spin-down models with the observed population of compact HMXBs. We describe the theoretical considerations in §2. In §3, we present the calculated results. Finally, we present a brief discussion and conclusions in §4.

2 MODEL

2.1 Spin Evolution

We consider a binary system consisting of a $1.4M_\odot$ magnetized NS and a massive donor star. The spin-down evolution of a NS in a binary system has been investigated by many authors. Generally speaking, the spin-down evolution of a NS before steady accretion occurs contains two phases: the pulsar phase and the propeller phase, as briefly presented below.

Case 1: the pulsar phase

Following its birth in a supernova explosion, the NS in a binary system first appears as a radio pulsar with a short spin period, if its radiation is strong enough to expel the wind material outside the Bondi accretion radius $r_G = 2GM/v_\infty^2$ (Bondi & Hoyle 1944) (G , the gravitational constant, M , the mass of the NS and $v_\infty = 10^8 v_8$ cm s^{-1} , the relative wind velocity at the neutron star’s orbit), or the radius of the light cylinder, $r_{lc} = cP_s/2\pi$. Magnetic dipole radiation and/or energetic particle emission result in the spin-down of a NS:

$$I\dot{\Omega}_s = -\frac{2}{3}\frac{\mu^2\Omega_s^3}{c^3}, \quad (1)$$

where I , the moment of inertia, $\mu = 10^{30}\mu_{30}$ G cm³, the magnetic dipole moment, and Ω_s , the angular velocity of the neutron star, respectively.

The pulsar phase will end either when the wind plasma penetrates inside the light cylinder radius r_{lc} or when the pressure gradient dominates at large radius. The corresponding transitional spin period P_{ab} derived by balancing radiation pressure from the pulsar with the stellar wind ram pressure at r_{lc} and P_{ac} obtained as the outer boundary R_a of the envelope approaches r_G can be described,

$$P_{ab} \simeq 0.8\mu_{30}^{1/3}\dot{M}_{15}^{-1/6}(M/M_\odot)^{1/3}v_8^{-5/6}\text{ s}, \quad (2)$$

$$P_{ac} \simeq 1.2\dot{M}_{15}^{-1/4}\mu_{30}^{1/2}v_8^{-1/2}\text{ s} \quad (3)$$

(Davies & Pringle 1981), where $\dot{M} = 10^{15}\dot{M}_{15}$ g s^{-1} , the accretion rate of the NS.

Case 2: the propeller phase

The propeller phase begins when the pulsar phase breaks down if the magnetospheric radius $R_m =$

$[\mu^4/(2GM\dot{M}^2)]^{1/7}$ is larger than the corotation radius $R_c = (GM/\Omega_s^2)^{1/3}$. The angular momentum of the NS is taken away from the NS surface when the infalling plasma is ejected outward because the centrifugal barrier inhibits further accretion. Although many authors (e.g. Pringle & Rees 1972; Illarionov & Sunyaev 1975; Davies & Pringle 1981; Wang & Robertson 1985; Ikhsanov 2001; Bozzo, Falanga & Stella 2008; Shakura et al. 2012) have investigated the propeller effect extensively, the efficiency of angular momentum loss during the propeller phase is still uncertain.

Davies & Pringle (1981) suggested that the propeller phase can be divided into two subphases: supersonic propeller phase and subsonic propeller phase.

(a) The NS will enter the supersonic propeller phase when the angular velocity, Ω_s , of the neutron star is large enough so that $r_c\Omega_s \gg c_s(r_c)$, where r_c is the inner boundary, $c_s(r_c)$ is the sound speed at the radius of r_c . The spin-down torque is

$$N = -8 \times 10^{31} \dot{M}_{15} v_8^2 \Omega_s^{-1} \text{gcm}^2 \text{s}^{-2} \quad (4)$$

(case c of Davies & Pringle 1981). The typical spin-down time-scale is

$$\tau = 1.6 \times 10^7 \dot{M}_{15}^{-1} v_8^{-2} I_{45} P_0^{-2} \text{yr}. \quad (5)$$

The spin-down of supersonic propeller phase process ends until P_s reaches the equilibrium spin period

$$P_{\text{eq}} = 23 \mu_{30}^{2/3} \dot{M}_{15}^{-1/3} v_8^{-2/3} \text{s}. \quad (6)$$

(b) Davies & Pringle (1981) suggested that accretion is unlikely to take place unless the material outside the magnetosphere can cool. Therefore, the NS spins at a subsonic speed and continues to lose rotational energy. The spin-down torque of subsonic propeller phase is

$$N = -1.2 \times 10^{36} \mu_{30}^2 (M/M_\odot)^{-1} P_0^{-3} \Omega_s^{-1} \text{gcm}^2 \text{s}^{-2} \quad (7)$$

(case d of Davies & Pringle 1981). The typical spin-down time-scale is

$$\tau \simeq 10^3 \mu_{30}^{-2} (M/M_\odot) P_0 I_{45} \text{yr}. \quad (8)$$

The spin-down of subsonic propeller phase process ends until P_s reaches P_{br}

$$P_{br} = 60 \mu_{30}^{16/21} \dot{M}_{15}^{-5/7} (M/M_\odot)^{-4/21} \text{s}. \quad (9)$$

Some authors proposed a different spin-down model for the propeller phase (Wang & Robertson 1985; Dai, Liu & Li 2006; Jiang & Li 2005; Ikhsanov 2001). They assumed that the plasma is accelerated outward with the corotation velocity at R_m , and the spin-down torque is

$$N = I \dot{\Omega}_s = -\dot{M} R_m^2 \Omega_s. \quad (10)$$

The typical spin-down time-scale $\tau = |\Omega_s/\dot{\Omega}_s|$ can be estimated to be

$$\tau \simeq 2.2 \times 10^4 \mu_{30}^{-8/7} \dot{M}_{15}^{-3/7} (M/M_\odot)^{2/7} I_{45} \text{yr} \quad (11)$$

(Dai, Liu & Li 2006). The process of spin-down ceases when P_s reaches the equilibrium spin period

$$P_{\text{eq}} \simeq 17 \mu_{30}^{6/7} \dot{M}_{15}^{-3/7} (M/M_\odot)^{-5/7} \text{s}. \quad (12)$$

Mori & Ruderman (2003) suggested that many proposed propeller spin-down models can be classified by two parameters. In these models, the spin-down torque is

$$N = I \dot{\Omega}_s = -\dot{M} R_m v_m \mathcal{M}^\gamma, \quad (13)$$

where \mathcal{M} is the Mach number defined as the ratio of incoming medium velocity to NS spin-velocity at the magnetosphere boundary : $\mathcal{M} \equiv R_m \Omega/v_m$. Proposed propeller models have γ with the value of -1, 0, 1 and 2.

Steady wind accretion onto the surface of the NS occurs when $P > P_{\text{eq}}$. However, the present spin periods of wind-fed X-ray pulsars are not significantly different from the P_{eq} . So we stop the calculations when either P_{eq} is reached within the main sequence lifetime or the optical star evolves off the main sequence. In the present paper, the narrow HMXBs with Roche-lobe overflow are never considered because the accreting material is most likely to come from an accretion disk. **For wind-fed systems like Vela X-1, numerical calculations (e.g. Fryxell & Taam 1988; Matsuda et al. 1992; Anzer & Börner 1995; Ruffert 1999) suggest that there are no significant angular momentum transfer onto the neutron star when radially expanding wind matter is transferred onto the neutron star. This may lead to only small deviation from the instantaneous (equilibrium if reached) spin periods when the accretion phase starts. A random walk in their spin frequencies with alternating spin-up and spin-down (Bildsten et al. 1997) is shown by CGRO/BATSE observations .**

2.2 Evolution of the mass-flow rate onto NS

We used the evolutionary population synthesis code developed by Hurley et al. (2000, 2002) to explore the spin-down rate of a NS in a binary system. The evolution of single stars with binary-star interactions, such as mass accretion, mass transfer, common-envelope (CE) evolution, collisions, supernova kicks, angular momentum loss mechanisms and tidal friction, is included in this code. The parameters we adopted are mostly the same as those described by Hurley et al. (2002). The primary-mass (M_1) distribution is the initial mass function of Kroupa, Tout & Gilmore (1993). A uniform distribution of the mass ratio $0 < q \equiv M_2/M_1 \leq 1$ is taken between 0 and 1 for the secondary star (of mass M_2). For the binary separation a , we take a uniform distribution in $\ln a$ (**natural logarithm of a**). We assume that one binary with $M_1 \geq 8M_\odot$ is born in the Galaxy per year, which gives the star formation rate $S = 7.6085 \text{ yr}^{-1}$. During the SN explosions, a kick velocity with the Maxwellian distribution is imparted on a NS with a mean of 265 km s^{-1} (Hobbs et al. 2005). Hurley et al. (2002) presented specially the treatment of Roche-lobe overflow (RLOF) mass transfer in the primordial binary and the stability criterion of mass transfer is described briefly here. According to whether the primary stays in thermal equilibrium when it loses mass, and the radius of the primary increases faster than the Roche-lobe, mass transfer through RLOF takes place on either a thermal, nuclear, or dynamical time-scale. Stars with deep surface convective zones—for instance, giants or naked helium giants—will enter a CE evolution because they are generally unstable to dynamical-timescale mass loss. Eddington accretion rate limits the stable mass accretion rate of the secondary star. We haven't considered the situation that the secondary may be spun up and become a Be star as it accretes enough mass because the origin of Be phenom-

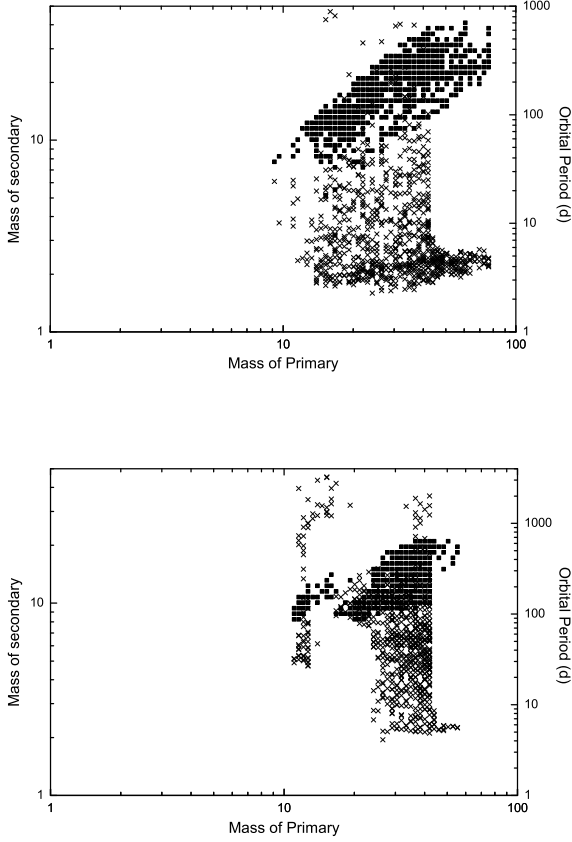


Figure 1. The region of parameter space from which NS high-mass binaries form. a) The mass transfer before primary star core-collapsing is dynamically stable; b) That mass transfer is dynamically unstable and thus the progenitor binary has evolved through a CE phase. Filled squares denote the mass distribution, while crosses denote the primary mass-orbital period distribution. The CE efficiency factor is adopted as a typical value $\alpha = 1.0$.

ena is still unclear and it is hard to give a model of the mass transfer processes in Be/X-ray binaries. The common envelop efficiency parameter α was set at $\alpha = 1$ as a typical value and we varied it from 0.1 to 2 in our calculations (Dewi & Tauris 2000; Tauris & Dewi 2001). The region of the parameter space from which NS high-mass binaries form is shown in Fig. 1. We can also derived other binary parameters, such as the surface temperature, luminosities, and radii of the companion stars. The mass loss rates from the companion stars and the mass flow rates onto the NSs can be evaluated by using these parameters.

To compare the observed properties of compact wind-fed NS HMXBs, we have calculated the number of the compact wind-fed NS HMXBs with $P_{orb} < 10$ days. The mass-loss rate \dot{M}_2 was presented by Nieuwenhuijzen & de Jager (1990):

$$-\dot{M}_2 = 9.6 \times 10^{-15} R_2^{0.81} L_2^{1.24} M_2^{0.16} M_\odot \text{yr}^{-1}, \quad (14)$$

where R_2 and L_2 are the radius and luminosity of the donor star. We evaluate all the physical quantities in Eq. (14) in solar units. The wind density ρ_w at the orbit of the NS by

assuming that the stellar wind expands isotropically at a speed of v_w , is

$$\rho_w = -\dot{M}_2 / (4\pi a^2 v_w), \quad (15)$$

and the mass infalling rate onto NS is roughly described by

$$\dot{M} = \pi r_G^2 \rho_w v_\infty \quad (16)$$

(Bondi & Hoyle 1944).

3 RESULTS

We calculated the evolution of spin and the statistical properties for compact wind-fed X-ray pulsars in NS binary systems based on the theoretical models presented in §2. For the initial NS magnetic fields B we assumed that $\log B$ is distributed normally with a mean of 12.5 (**the typical magnetic fields of such pulsars are 3×10^{12} G**) and a standard deviation of 0.3. No field decay was considered. We stopped our calculations for the spin evolution when either P_s reaches P_{eq}/P_{br} (depending on whether the subsonic propeller phase exists) or the companion star began to evolve off the MS, for the reasons described **above**.

We adopt a variety of models (see Table 1), each with different assumptions for the spin-down rate and parameters that govern the evolutions in the calculations. In Table 1, DP81, WR85, MR03 represent the spin-down models described by Davies & Pringle (1981), Wang & Robertson (1985), and Mori & Ruderman (2003) respectively. NO in Table 1 describes the situation when the subsonic propeller phase doesn't exist. We consider the only situations when $\gamma = -1$ and $\gamma = 0$ for the spin-down model described by Mori & Ruderman (2003) because the spin-down model corresponds to WR85 and DP81 when $\gamma = 1$ and $\gamma = 2$. Figure 2 shows evolution of the NS spin period (with the same initial parameters of the binary) in a binary system for different models, which indicates that it may induce a longer spin period of NS when the subsonic phase exists.

Table 2 summarizes the calculated numbers of compact ($P_{orb} < 10$ days) wind-accreting NS HMXBs in our Galaxy for different models (listed in Table 1). The observed compact ($P_{orb} < 10$ days) NS HMXBs are listed in Table 3 (Liu, van Paradijs, & van den Heuvel 2006; Wang 2010; Reig et al. 2009; Wang & Chang 2012, 2013; Pearlman, Corbet & Pottschmidt 2013; Manousakis, Walter & Blondin 2012). We find that the spin-down rate in the supersonic propeller phase given by Davies & Pringle (1981) is too low to produce the observed population of compact HMXBs no matter whether the subsonic propeller exists or not. Our calculation shows the similar conclusion for the spin-down model described by Mori & Ruderman (2003) when $\gamma = -1$. We also find that the model suggested by Wang & Robertson (1985), Dai, Liu & Li (2006) and Jiang & Li (2005) with a larger spin-down rate than that given by Davies & Pringle (1981) can predict a reasonable number of observed wind-fed compact NS HMXBs no matter whether the subsonic propeller phase exists or not. We can also derive the similar conclusion for the spin-down model described by Mori & Ruderman (2003) when $\gamma = 0$.

To compare the calculated results with observations of compact wind-fed NS HMXBs, we show the distributions

Table 2. Predicted present numbers in our Galaxy of Compact ($P_{orb} < 10$ days) wind-accreting NS-HMXBs.

Model	A1	A2	A3	A4	A5	B1
Number	9.1×10^{-3}	9.2×10^{-3}	1.3×10^{-2}	5.3×10^{-1}	0	6.4
Model	B2	B3	B4	B5	B6	B7
Number	9.9	1.9	6.5	10.3	6.7	13.6
Model	C1	C2	C3	C4	C5	C6
Number	0	4.8	0	4.9	0	4.9

Table 3. Observed compact ($P_{orb} < 10$ days) NS-HMXBs.

Name	$P_{orb}(\text{d})$	$P_{pulse}(\text{s})$	Name	$P_{orb}(\text{d})$	$P_{pulse}(\text{s})$
1WGA J0648.0-4419 RX J0648.1-4419	1.55	13.1789	4U 0900-40 Vela X-1	8.96	283
4U 1119-603 Cen X-3	2.09	4.84	4U1538-52	3.73	529
IGR J16320-4751 AX J1631.9-4752	8.96	1309	4U 1700-37 ^a	3.41	
EXO 1722-363 IGR J17252-3616	9.74	413.9	SAX J1802.7-2017 IGR J 18027-2016	4.6	139.61
XTE J 1855-026	6.067	361	4U 1907+09 H 1907+097	8.38	438
4U 1909+07 X1908+075	4.4	604.68	4U 2206+543 ^b 3A 2206+543	9.57 ^c	5560
IGR J16493-4348	6.78	1093	IGR J16418-4532	3.74	1240
IGR J17544-2619	4.9	71	IGR J01583+6713	3-12 ^d	469

^a $M_X = 2.44$, low mass black hole candidate?

^b 392 s pulsation (?)?

^c a new periodicity of 16.25 d recently suggested by Reig et al. (2009)

^d a possible orbital period in the range 3-12 days suggested by Wang (2010)

of those neutron star binaries with $P \gtrsim P_{eq}$ and of the observed HMXBs in a $P_s - P_{orb}$ diagram (see Figure 3 and 4). The relative numbers of binary systems are indicated by the darkness of the shading. Diamonds and pluses mark the supergiant wind-fed HMXBs and supergiant fast X-ray transients, respectively, and crosses are for Roche lobe overflow systems. The two joined triangles represent 4U 2206+54 for the two suggested orbital periods (Reig et al. 2009). The two joined asterisks represent IGR J01583+6713 for a possible orbital period in the range 3-12 days suggested by Wang (2010). Figure 3 presents the calculated results for those models when subsonic propeller phase exists. According to our calculations, we note that the spin periods are too large to compare with the observations no matter which values the parameters take when subsonic propeller phase exists. That is, no spin-down model can produce the observed distribution of compact wind-fed NS HMXBs in a $P_s - P_{orb}$ diagram when subsonic propeller phase exists.

Figure 4 shows the calculated results for all the spin-

down models with different values of the parameter α , v_8 , and \dot{M} when the subsonic propeller phase doesn't exist. If v_8 is increased from 1 to 2, the mass flow rates onto the neutron stars are lower by a factor of ~ 16 in accordance with equations (15) and (16), further inducing longer equilibrium periods which can be seen clearly in Figure 4. The results also indicate that changes in the parameters α and \dot{M} do not significantly influence the final outcomes, which is consistent with the observed distribution of compact wind-fed NS HMXBs in our Galaxy in a $P_s - P_{orb}$ diagram. So, we can conclude that the subsonic propeller phase may not exist at all from our calculated results plotted in Figure 3 and 4.

4 CONCLUSIONS AND DISCUSSION

We have calculated the evolution of spin and the statistical properties for compact wind-fed X-ray pulsars in NS binary

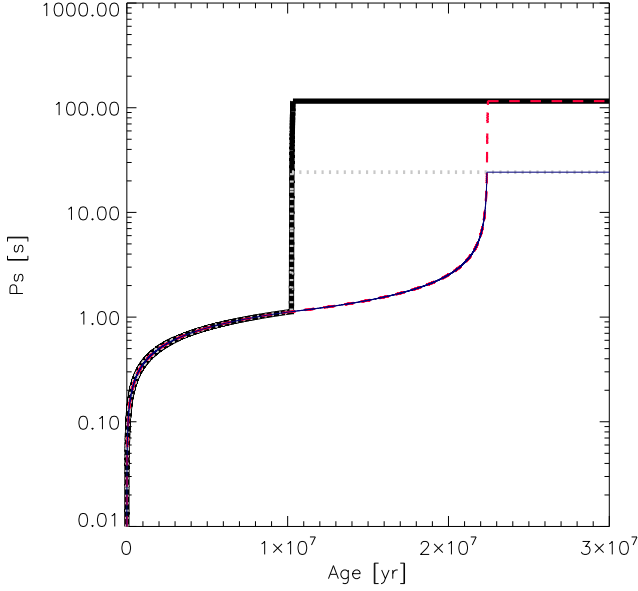


Figure 2. An evolutionary example of compact NS-HMXBs. Evolution of NS spin period in a binary system with the same initial parameters of the binary for model A1 (red dashed line), model A2 (thin blue line), model B1 (thick black line), and model B6 (thick gray dotted line). The evolution begins after the birth of the NS.

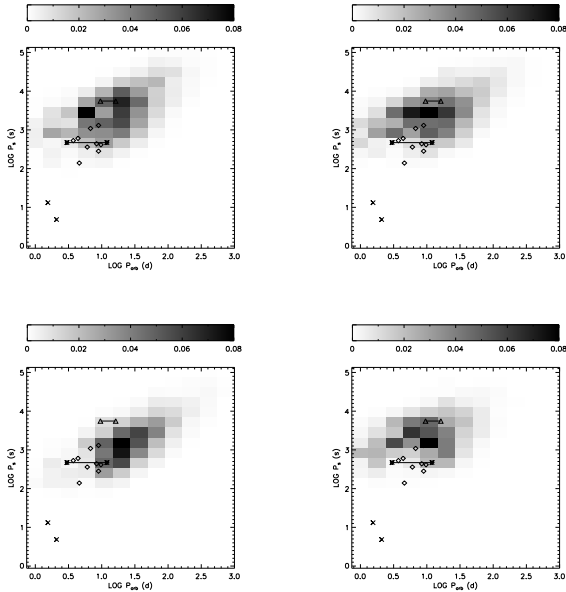


Figure 3. The $P_s - P_{orb}$ distribution of wind-fed HMXBs. Diamonds and pluses mark the supergiant wind-fed HMXBs and supergiant fast X-ray transients, respectively, and crosses are for Roche lobe overflow systems. The two joined triangles represent 4U 2206+54 for the two suggested orbital periods (Reig et al. 2009). The two joined asterisks represent IGR J01583+6713 for a possible orbital period in the range 3-12 days suggested by Wang (2010). Top, model B1 (left) and model B2 (right); bottom, model B3 (left) and model C2 (right).

Table 1. Model parameters for binary population synthesis. The items of “sup” and “sub” denote the adopted NS spindown models for the supersonic propeller and subsonic propeller phases, respectively. $\dot{M} = 1$ or 3 denotes the wind mass-loss rates assuming to be 1 or 3 times of the standard prescription we adopted in §2, respectively. v_8 is the wind velocity in unit of 10^8 cm.

Model	sup	sub	α	\dot{M}	v_8
A1	DP81	DP81	1	1	1
A2	DP81	NO	1	1	1
A3	DP81	NO	0.5	1	1
A4	DP81	NO	1	3	1
A5	DP81	NO	1	1	2
B1	WR85	DP81	1	1	1
B2	WR85	DP81	0.5	1	1
B3	WR85	DP81	1	3	1
B4	WR85	DP81	1	1	2
B5	WR85	NO	0.5	1	1
B6	WR85	NO	1	1	1
B7	WR85	NO	0.5	1	2
C1	MR03($\gamma = -1$)	DP81	0.5	1	1
C2	MR03($\gamma = 0$)	DP81	0.5	1	1
C3	MR03($\gamma = -1$)	NO	0.5	1	1
C4	MR03($\gamma = 0$)	NO	0.5	1	1
C5	MR03($\gamma = -1$)	NO	1	0.5	1
C6	MR03($\gamma = 0$)	NO	1	0.5	1

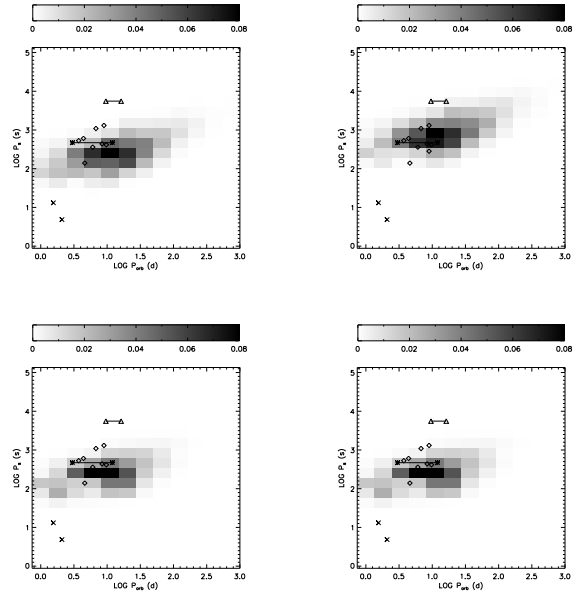


Figure 4. Same as Figure 3 but top, model B5 (left) and model B7 (right); bottom, model C4 (left) and model C6 (right).

systems. The numerical results presented in Table 2 show that the spin-down rate in the supersonic propeller phase given by Davies & Pringle (1981) is too low to produce the observed number of compact HMXBs no matter whether the subsonic propeller phase exists or not. The same conclusion can be derived for the spin-down rate in the supersonic propeller phase given by Illarionov & Sunyaev (1975) (the case of $\gamma = -1$ in Mori & Ruderman 2003). We also find

that the spin-down model proposed by Wang & Robertson (1985); Dai, Liu & Li (2006); Jiang & Li (2005) can predict a reasonable number which is consistent with the observations no matter whether the subsonic propeller phase exists or not. The same conclusion can be inferred for the spin-down rate in the supersonic propeller phase described by Davidson & Ostriker (1973) (the case of $\gamma = 0$ in Mori & Ruderman 2003). In order to investigate whether the subsonic propeller phase exists or not, we compare our calculated results with the observed particular distributions of compact supergiant HMXBs in the $P_s - P_{orb}$ diagram which has been described in Dai, Liu & Li (2006). From Figure 3 and 4, we can conclude that the subsonic propeller phase may not exist at all. The very long period, $P_s = 5560$ s, of 4U 2206+543, may be explained by a accreting magnetar model which allows it to be spun down efficiently by the propeller effect (Ikhsanov & Beskrovnaya 2010; Reig 2012; Wang & Chang 2013). However, the spin-down rate given by Davies & Pringle (1981); Dai, Liu & Li (2006); Jiang & Li (2005) and that given by Davidson & Ostriker (1973) in the supersonic propeller phase both seem reasonable to produce the observed distributions of compact supergiant HMXBs in the $P_s - P_{orb}$ diagram. We cannot conclude which spin-down rate seems more reasonable from our calculated results.

Our results are subject to some uncertainties. The different values of parameters α and \dot{M} do not have significant influence on the final outcomes (**e.g., the total number changes only by a factor of 2 or 3 even when the parameter α varies from 0.1 to 2, what's more, the different values of parameter α has little effect on the distributions in the $P_s - P_{orb}$ diagram**). The changes in the parameter v_s do not significantly influence the calculated number of compact NS HMXBs while it can induce longer equilibrium period with a larger wind velocity. This indicates that there may exist no subsonic propeller phase further. Aerts & Lamers (2003) have suggested that the wind velocity of supergiant increases with radius according to a β -law in some special condition, however, our calculations indicate that it does not significant affect our final results. We have also investigated the effect of the magnetic field. The models can produce more compact HMXBs (about ten times more compact HMXBs are produced when the initial NS magnetic field becomes ten times larger) and longer spin and orbital periods with a larger initial magnetic field. The results also support our conclusion that there may not exist subsonic propeller phase further. However, some authors have also proposed that the magnetic field of NS may decay during the evolution of the binary (Geppert & Rheinhardt 2001; Hollerbach & Rüdiger 2002; Zhang & Xie 2012). If we assume all the neutron star's magnetic field decays, our calculations indicate that it can produce less number of compact HMXBs and shorter spin and orbital periods while it has no significant effect on our conclusion. A number of authors have also suggested that some neutron stars receive low kick speeds of ≤ 50 km s^{-1} at birth (Pfahl et al. 2002; Podsiadlowski et al. 2004; Dewi, Podsiadlowski & Pols 2005). If all the neutron stars were born with such small kicks, our calculations indicate that there should have been about 4-5 times more compact HMXBs produced. However, it has no significant effect on the distribution in the $P_s - P_{orb}$ diagram.

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